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# Seasonal Surface Loading helps Constrain Short-term Viscosity of the Asthenosphere

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**Key Points:**

- Chanard et al. (2018) find globally-averaged transient asthenospheric viscosity is at least 5e17 Pa s.
- Lower values found by post-seismic studies must arise from localized anomalies or misinterpretation of afterslip or shear zone motion.
- Longer time series and finer spatial detail of surface mass loads are needed to tighten this constraint and improve depth resolution.



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## Abstract

Earth materials may display a range of rheological behaviors at different depths and over different timescales. The situation is particularly complex for post-seismic relaxation in the uppermost mantle and lower crust, where it can be difficult to distinguish widespread viscous behavior from earthquake afterslip or localized deformation in shear zones over timescales of weeks to decades. By analyzing geodetic observations of seasonal surface mass loads and Earth's surface deformation in response, Chanard et al. (2018) have established a globally-averaged lower bound of $5\times10^{17}$ Pa s for the transient viscosity of a Burgers-rheology asthenosphere. This implies that lower viscosities inferred by some studies of post-seismic relaxation must result from local departures from this global value, or be an artifact of additional afterslip or shear zone deformation.


At timescales of seconds to minutes, encompassed by global seismological observations, Earth behaves as an almost perfectly elastic body displaying only slight attenuation of seismic waves as they propagate. In contrast, at the timescales of thousands to millions of years associated with major glacial episodes and planetary-scale deep Earth processes, the "solid" Earth is dominated by the viscous deformation of its mantle which is overlain by a relatively thin lithosphere showing nearly-elastic behavior only to depths of the order of several tens of kilometers. Between these end-member timescales, phenomena such as tidal deformation, deformation due to shifting hydrological, atmospheric and oceanic mass loads on Earth's surface, and post-seismic relaxation, occur in a way that is neither purely elastic nor purely viscous. In some cases this transient behavior may be characterized by a type of viscoelastic rheology with an effective short-term viscosity that is lower than the long-term value, but studies involving different causing mechanisms and at different temporal and spatial scales show wide variation in the values of these parameters. This variation is particularly acute for observations of post-seismic relaxation, where it can be difficult to distinguish pervasive viscous processes from more localized shear or afterslip. In a recent article, Chanard *et al.* (2018) offer new interpretations of seasonal surface mass loading at regional to global spatial scale which may shed light on these discrepancies.

At seismic wave periods, Earth materials approximate some combination of a perfectly elastic solid with a Kelvin-Voigt body showing strain retardation (Figure 1), in other words a standard linear body dominated by its instantaneous elastic component. GNSS-observed displacements due to surface mass loading resulting from the semi-diurnal and diurnal ocean tides show that this near-elastic behavior persists to daily timescales, although with significant reduction of the shear modulus in the asthenospheric upper mantle compared with its value at seismic periods (Bos et al., 2015; Ito & Simons, 2011). Whilst exhibiting the spatial variability necessary for sensitivity to Earth's rheology at the appropriate depths, such observations are therefore too short in period to impinge *directly* on the question of post-seismic deformation in the Earth's lower crust or asthenosphere. In contrast, the Earth's body tides, which likewise show evidence of lower mantle anelasticity at semi-diurnal right through to decadal timescales (Benjamin et al., 2006; Kang et al., 2015), are large-scale phenomena and are therefore largely insensitive to the rheology of the outermost few hundred kilometers of the Earth.

In the long term, the lithosphere retains its elasticity, but stresses in lower in the mantle, and possibly also in the lower crust, will relax by viscous flow; this rheology can be approximated by the steady-state behavior of a Maxwell body (Figure 1). This approximation, of Maxwell behavior, is used by most models of glacial isostatic adjustment (Spada et al., 2011). Steady-state upper mantle viscosities inferred in this way, for the regions of the major ice sheets at the Last Glacial Maximum, mostly range from $10^{20.5}$–

$10^{22}$ Pa s (e.g. Ivins & James, 2005; Milne et al., 2001). However, significant regional variations due to temperature, grain size and water content are expected (e.g. Barnhoorn et al., 2011), and viscosities as low as $10^{18}$–$10^{19}$ Pa s have been predicted (Ivins & James, 1999) and observed (Nield et al., 2014) in localized responses to decadal to centennial scale changes in ice mass loading. This observed range of viscosities provides the longer-term context for observations of post-seismic deformation, at spatial scales which are comparable with those of the effects of larger earthquakes.

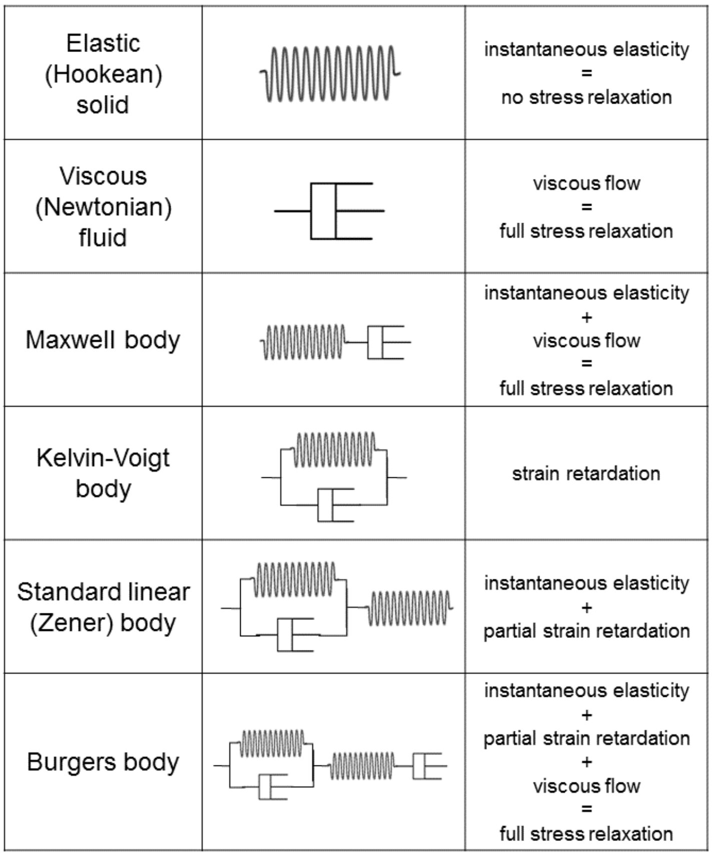


**Figure 1**. Simple 1-D mechanical analogues for fundamental rheological models, constructed as combinations of perfectly elastic springs, and leaky pistons containing viscous fluid, joined by rigid rods (after Zschau, 1983).

Post-seismic relaxation occurs over weeks to decades following a major earthquake, at the nexus of the timescales associated with the above-mentioned rheological models. A Burgers rheology is often adopted for modelling the lower crust and upper mantle (e.g. Pollitz & Thatcher, 2010), as it includes separate transient and steady-state viscosities which may both have significant impact. However, there can be ambiguity between the surface displacements caused by this viscous behavior and those due to post earthquake afterslip or shear zone deformation in the immediate vicinity of the fault. This problem is particularly acute if the geodetic measurements are only available in the near field (Ingleby & Wright, 2017), or, for large subduction zone earthquakes, if seafloor geodesy observations are not available to sample the oceanward side of the region (Hu et al., 2016; Sun et al., 2014). But even if afterslip and bulk viscous behavior are parameterized individually in a joint inversion, short observational time series spanning only the few years following an earthquake tend to favor models which primarily reflect the rheology of the weaker fault zone rather than the surrounding material (Yamasaki et al., 2014). Asthenospheric transient viscosity values from post-seismic studies, which are in some cases as low as $10^{17}$ Pa s, could therefore be unrepresentative of the asthenosphere as a whole. However, without estimates over similar timescales but from outside of tectonically active zones, it is impossible to distinguish material spatial heterogeneity from temporally more complex behavior such as additional transient viscosities.

Chanard et al. (2018) have brought a new dataset to bear on the problem of the globally-averaged viscosity of the uppermost mantle: surface mass loading at seasonal timescales, observed by the Gravity Recovery and Climate Experiment (GRACE) satellite system since 2002. Previous studies have used *elastic* Earth models to predict the surface displacements associated with this mass load and shown moderate agreement with geodetic measurements. Now, Chanard et al. have shown that using a *viscoelastic* (Burgers body) model will result in significant differences in the surface displacements compared with the elastic case, notably in their horizontal components, for a range of transient viscosity and rigidity parameter values. Using a long-running and populous global dataset of GNSS coordinate time series, they have then shown that the transient viscosity must be at least $5\times10^{17}$ Pa s (for a steady-state viscosity of $10^{19}$ Pa s), and the Burgers transient rigidity at least one-fifth of the steady-state rigidity.

This shows that at roughly annual timescales, the asthenosphere's transient viscosity is generally higher than that apparent in the vicinity of many recent large earthquakes. This is not necessarily in conflict with the underlying observations: Chanard et al.'s transient viscosity bound should be interpreted as a global value, not restricted to tectonically active regions, which may allow the existence of afterslip or shear zones to be deduced when the apparent local transient viscosity derived from post-seismic observations lies below this limit.

Longer-term surface mass load and displacement datasets may soon allow the viscosity bound to be set higher, once the time series are long enough that viscoelastic response to multi-year loading signals can be observed. Further interest will emerge as finer spatial detail of the load and response can be resolved. At present, asthenospheric rheology averaged over wide areas can be resolved from GRACE observations with corresponding spatial scale (several hundred to a thousand kilometers), but greater sensitivity to rheology at asthenospheric depths, and distinguishing of putative lower crustal channel flow, will require accurate observations of the surface mass load and response at spherical harmonic degrees of 100 or greater (Martens et al., 2016) which GRACE cannot provide. GNSS site coverage has increased dramatically in the last decade and will allow this spatial resolution in many regions, but the challenge remains to characterize seasonal and longer-term surface mass loads at this level of detail.

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